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A paper read at the 158th Meeting of the American Institute of Electrical Engineers, New York and Chicago, November 22, 1901.

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DISTRIBUTION OF ELECTRICAL ENERGY IN LARGE CITIES.

BY LOUIS A. FERGUSON.

With the trend of modern times towards consolidation of lighting, power and transportation properties, the system of distribution of electrical energy, in large cities especially, is daily becoming a more important question, involving many perplexing problems and considerations. Were one given the problem of determining the system in an imaginary city fully developed in its business and residential portions, its growth matured and freed from the pioneering and bad engineering of the promotion days of electricity, the question would be a comparatively easy one. But as our only living ex-president has said, it is a condition and not a theory which confronts us.

Nearly every city has granted franchises to many companies having varying degrees of financial and engineering ability so that those who are ultimately engaged in consolidating the physical properties usually find it advisable to adapt their engineering to existing conditions abandoning as little as possible of the investment made by those which they have absorbed. Not only must be considered what has been done in the past but also the possible development of the future, so that the remodelling shall not necessarily be that which might appeal most strongly to the conditions of the moment, but of the future; for our investments, let us hope, are made not only for the present, but for the future.

The developments of the last few years have determined conclusively that the old method of installing a multiplicity of steam

generating stations scattered throughout the city and furnishing electricity for lighting and power in the surrounding district is no longer advisable. We find the more progressive companies abandoning their smaller plants as generating stations, converting some into sub-stations and centralizing the generation of electrical energy in one or two large power stations located preferably on a water front and having direct communication with two or more railroads bringing coal from different sections of the country.

There are several instances in Europe, as well as in America, of lighting and railway companies providing for their future growth by the erection of large central power-houses of from 50,000 to 100,000 horse-power ultimate capacity. In some cases these new power-houses supplant entirely the older stations, and in others the older stations are retained intact, and are used during the peak hours of the winter months as auxiliary generating stations. This latter method is usually the more economical, since it saves a large additional investment which would have to be made for use during only a few hours daily in two or three winter months. Although the cost of generation per kilowatt hour in these old stations will be very high as compared with that of the new station, it is still wise to use them as auxiliaries to the main station or sub-station even though they be non-condensing plants, because their output being a small percentage of the total, the excess cost of their operating will be less than the interest and depreciation on the investment required in new station and sub-station equipment and transmission lines to supplant them.

The choice of a site for the main power-house (water and coal facilities being equal in each case) will depend upon the combined cost of the land and the transmission of the total capacity to the sub-stations with the advantage in favor of the site nearest to the point of greatest delivered output; that is, the preference should be given to that site where the value of the land forms a larger proportion of the total than does the cost of the transmission. The less the cost of the transmission the less its length, and therefore the less cable and conduit to maintain. Since the territory to be supplied in any large city from a central power-house for general distribution of electricity for all purposes is so extensive, the adoption of a high-pressure alternating current is necessary for transmission. There may be cases in which it is possible to obtain a site sufficiently large for a prin-

cipal station near enough to the center of greatest load to warrant the use of double current generators if direct current forms the basis for lighting and power distribution, and the energy supplied for railway purposes is relatively small. In any new principal station the generators should be of the same frequency even if it is advisable owing to local conditions that one or more be double current machines. It is always conducive to economy,

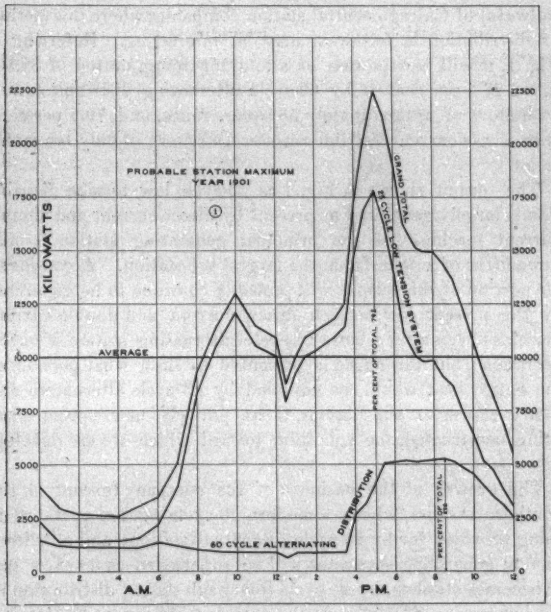

FIG. 1.

flexibility of operation and minimum initial investment that all the generators be arranged for parallel operation. The installation of both 60 and 25-cycle generators in the same station in a large city should be avoided, as the greatest economy is only possible in a station generating by one class of apparatus.

The determination of the class of current we shall generate depends entirely on the class of current we distribute. Consid-

ering the question for a large city from the broadest standpoint and judging by experience with the advantages and limitations of both forms of distribution, I would recommend direct current for the lighting and power work of the strictly business and city residential districts, and alternating current for the less closely built residential districts with their local business incident thereto, as well as for the actual suburban territory of the city.

An analysis of the lighting and power output (not including railways) of Chicago central station companies where this method of distribution is followed, may be interesting. Referring to Fig. 1, it will be seen that of a total maximum output of 22,500 K. W., 23.4 per cent. is by 60-cycle alternating distribution over a territory of approximately 58 square miles, and 79.5 per cent. is by direct current distribution over a territory of only ten square miles.

The output shown in Fig. 1 as 25-cycle low tension distribution is largely generated at present by direct current and double current machines, as the principal generating station is only three-fifths of a mile from the largest sub-station. A considerable portion of this output will probably continue to be generated by the present low tension direct current and double current machines even after a large 25-cycle alternating station is put in operation; but this curve is presented to show what portion of the entire load would be supplied by 25-cycle alternators and rotary converter sub-stations, if an entirely new system were being constructed, the condition toward which we are developing.

The growth of the business of the company (except in the Southern District, where a modern 60-cycle station operates) is being provided for by 25-cycle rotary sub-stations and all direct current generating apparatus will be superseded as it wears out or becomes obsolete, by 25-cycle rotary sub-station distribution in one low tension district. As the outlying residence districts become more general consumers of electricity, they are changed over to low tension direct current, and all new development in the Northern and Western Districts is supplied by motor generator sets receiving 25-cycle current from the main generating station and delivering 60-cycle current to the distribution lines.

Reference to Fig. 2 will show how the maximum load of the low tension direct current distribution was provided for last winter. It will be noticed that the rotary converter output formed

a very small portion of the total, but in this winter's maximum we expect to turn out about three times the amount of rotary output, while the direct current delivered to the distribution mains directly from the continuous current generators will show only a slight increase. The storage battery discharge will show about 100 per cent. increase. The growth in the rotary and battery

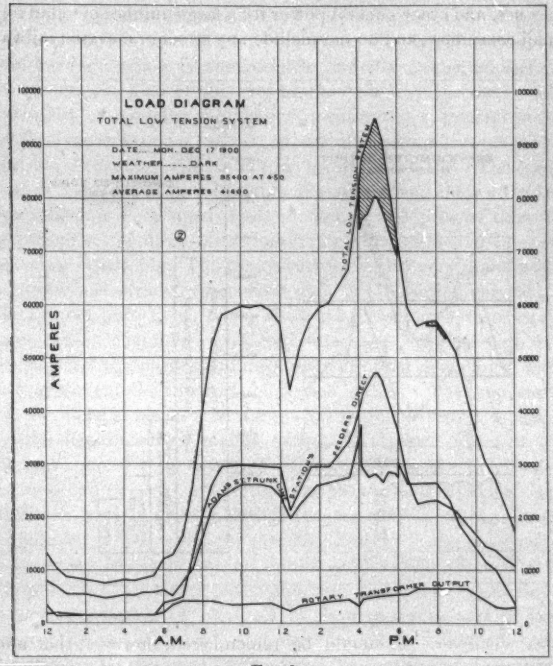

FIG. 2

outputs and the practical standstill in direct current generating output gives some conception of how we are working towards the idea of 25-cycle alternating supply from one large station to a number of combination rotary and battery sub-stations. To effect a change of this kind without sacrificing the value and use of our present investment in direct current generating stations will take several years.

In determining what shall be the general system of distribution, a study of the present conditions and future possibilties of electrical consumption must first be made, and the system chosen should be one that will best suit these conditions. Fig. 3 shows the relative quantities of light and power consumed monthly by the customers of the two Chicago companies. These curves represent only the actual power business for elevators and small factory use, and other general power for a large number of relatively small consumers, and do not include any street or elevated railway

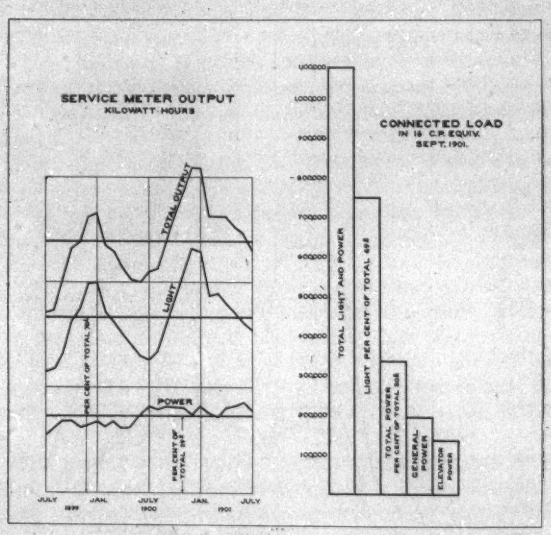

FIG. 3.

work whatever. It should be remembered, however, that any system of generating or supply which does not take into consideration this factor is not comprehensive enough to provide for the future conditions of our American cities, which will undoubtedly involve the supplying of electrical energy for lighting, general power and local transportation work from one or more large generating plants.

With the percentage of power as high as 30 per cent. (shown in Fig. 3), even when general power only is included, the great

importance of selecting a system of generation and distribution, which is well adapted for power as well as lighting supply, will be thoroughly appreciated. It is also important to note that the power curve shows no month of the year higher than another, as the light does, and also that a daily power curve shows practically a straight line from 8 A. M. to 6 P. M. every business day of the year, while the light load shows a sharp peak of only from one to two hours' width every winter day. The importance of the power business leads us then to adopt the three-wire direct current system for distribution in the business and city residential sections shown on the map of the city as the "Central District." The feasibility of applying the direct current motor to general power work is much superior to that of the alternating current motor, and the disturbing effects on line pressures are less. The initial cost of the direct current motors themselves and their attendant equipment is very much less; in fact, at the present time the selling prices of three-phase motors in America are far in excess of being reasonable. The direct current is also very much better adapted to electric elevator work than is alternating current; at the present time there is no alternating current elevator equipment which could be considered fitted for first-class high duty service, and the progress in development of an economical alternating current elevator for any service is slow. The importance of the electric elevator to the central station company is shown by the diagrammatical representation of outputs. There it will be seen that the consumption of electrical energy by elevators alone is 12½ per cent. of the total output of the companies. Our ability to install an economical and successfully operating elevator equipment is frequently the deciding feature in the question involving the choice of central station service in preference to the installation of a private plant, and with its aid we are enabled in a large percentage of instances to show to the owners of large mercantile establishments and other buildings a decided saving by purchasing electrical service from the central station company for lighting, elevator and general power service when compared with the cost of operating an isolated plant using hydraulic elevators.

The development of the automobile and its extended use in the large cities has rendered necessary the installation of charging equipments at convenient points throughout the city. With direct current the problem of charging is simplicity itself, requiring

merely an outlet in one's stable or in the sidewalk or a charging post on the street corner. Where only alternating mains are found the installation of a charging equipment is not only very expensive in its first cost, requiring transformers, motor generator and suitable housing, but also expensive to operate, requiring a competent attendant to start and stop the apparatus; so that the net revenue to the central station company will at best be small, and often times the results of the operation will represent an actual loss.

The use of alternating current in the distribution system prohibits the use of storage batteries. Even assuming that the storage battery does not improve the economy of operating, still they are desirable wherever the service of the central station company is important. They may be adapted for use in various ways; in the central station itself when it is located at the electrical center; at the center of distribution for discharging during the peak; as auxiliaries in the rotary converter sub-stations for discharge use at the time of maximum load in the main central station, or at any time of break down of the transmission line feeding the sub-station. They may also be used in sub-stations in special districts where the load factor of the district is small, or midway between rotary sub-stations for purposes of regulation.

The greatest value of the storage battery, however, is its ability to carry us through an emergency which comes as a rule in an electric lighting or power plant with very little warning. The fully charged battery kept constantly floating on the system becomes the watchdog of the company's service, responding to a call automatically, keeping the pressure chart perfect despite blown out cylinder heads in the central station or failures in sub-station transmission lines.

The storage battery has a very distinct value, which is seldom recognized and employed to its full advantage, when located at the central distributing point of a system with feeders radiating to various points in the network. The battery may be provided with two or more end cell switches, so arranged that they may be connected in multiple and feed into the main distributing bus, or they may connect to one or more auxiliary bus bars with a different number of cells in series, feeding into each bus and thus providing two or more potentials at the center of distribution. It will be found that when only one pressure is maintained at the

center of distribution during the time of maximum load of a large district the pressure at the ends of the short feeders will be somewhat higher than the standard and they will be overloaded, and at the end of the long feeders the pressure will be lower and the

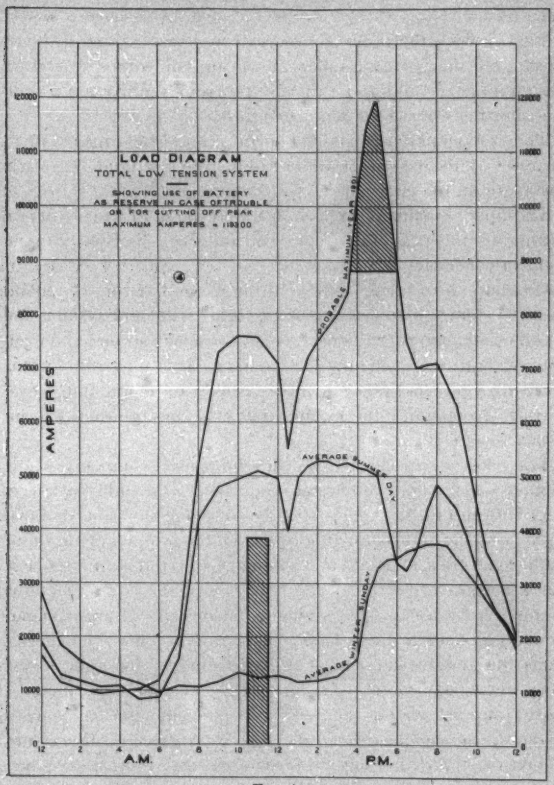

FIG. 4.

feeders underloaded, although the pressure variation at other times may be negligible. Under such conditions the storage battery becomes exceedingly valuable, for by arranging it to operate at two or more potentials, the long feeders may be connected

during the time of maximum load to the auxiliary bus or busses and additional current forced over them, utilizing their full capacity and maintaining a uniform feeder end pressure by means of an investment in end cells very slight as compared with the investment in additional feeders and mains to accomplish the same result.

Fig. 4 shows three curves, representing two extremes of daily output, one being the Sunday curve and the other the yearly maximum curve, and also a third curve, representing the form of the company's curve for about two-thirds of the year.

The rectangular crosshatched portion shows the capacity of the batteries at the one hour rate of discharge and might be placed anywhere on the curve.

The upper crosshatched portion shows the use of the battery in cutting off the peak, thus saving an otherwise necessary investment in generating plant.

Occasions have arisen where through the bursting of a boiler tube the storage battery has saved the direct current system from shut down by carrying the entire load for about an hour, allowing time for cutting out the disabled boiler. It is impossible in this curve to show the value of the battery in maintaining even pressure throughout the system, but it is one of the very important uses of the battery.

The battery capacity of the Chicago Edison Company is distributed over the entire low tension district. In addition to the three batteries in the Adams street sub-station, having a combined capacity at the eight-hour rate of 66,000 ampere hours, there are smaller batteries in three of the rotary sub-stations in the residence districts.

These batteries in the residence districts, of course, cannot economically cut off a residence load peak, because the latter is about four hours wide, but by discharging at the time of the down town peak, which is only between one and two hours in width, they are able to cut down the demand for three-phase current at the generating station. In this way they are as valuable on peak work as though they were located in the down town district, except that they do not save any investment in transmission line or sub-station apparatus.

Fig. 5 shows clearly the value of the storage battery in a motor generator sub-station operating an interurban railway. Its main function here is as a regulating battery used to take up the

fluctuations of the railway and keep a nearly constant load on the motor generators.

Having determined that direct current distribution is the most desirable for the central district of the city, and having shown that of the total maximum output of the lighting companies of the city, 79.5 per cent. is by direct current, even when the promising sections of the whole city are well covered by mains, it then becomes natural to choose a system of generation for the principal stations that is best adapted to the direct current distribution, as it represents such a large percentage of the total output. We, therefore, originally adopted in Chicago for trans-

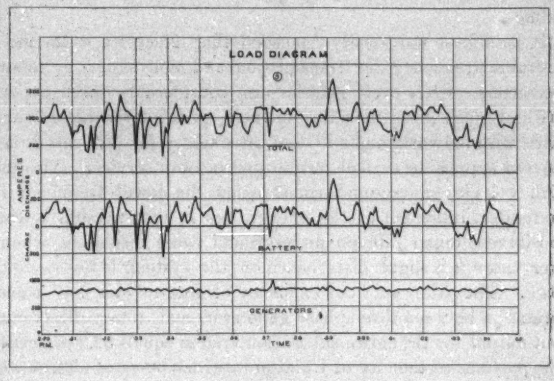

FIG. 5.

mitting to rotary converter sub-stations 25-cycle three-phase alternating current generated by double current machines at 160-volts alternating, arranged for stepping up to 4,500 and 9,000 volts. The reason for employing double current generators in preference to three-phase alternators generating the line voltage was because the principal station of the company was only three-fifths of a mile from the point of greatest direct current output. The double current machine, therefore, could be worked at best efficiency supplying the necessary three-phase current for the outlying rotary sub stations, the balance of capacity in the generators being used to feed directly into the low tension network thus working the generators at all times at full load.

There has just been started in operation in this station the largest double current machine which has yet been built. It has a nominal capacity of 2,500 K. W., with overload limit for peak work to 3,200 K. W., generating 300 volts direct current and 180 volts three-phase alternating. This machine is to run in parallel with the other double current and direct current machines in the station as well as in parallel with a new 3,500 K. W. three-phase alternator being erected beside it to generate 9,000 volts.

As we have reached the limit of available space in our principal plants for the central district it is probable that all additional generating plants will be by 25-cycle three-phase alternators generating directly 9,000 volts, the transmission line voltage.

It is almost universally conceded that 25-cycles is the most desirable frequency for transmission and conversion by rotary converters. Sixty-cycle rotaries are considerably more expensive and much less satisfactory in their operation for the ordinary three wire network, and still less satisfactory for 500 volt direct current supply for surface or elevated railway service. Also for high voltage undergound transmission the lower frequency is preferable, inasmuch as the energy loss in transmission is less, and its resultant strain on underground cable insulation, whenever there is a slight disturbance on the system, is less troublesome. The kilowatt hour efficiency of transmission and transformation between three-phase generators and rotary direct current output for the entire sub-station system equals 82.2 per cent. The portions of the city of Chicago in which 60-cycle alternating current is employed in the distribution system are shown on the map as Northern, Western and Southern districts. These territories were when acquired partially covered by single-phase 1,000-volt 125-cycle circuits. [See Fig. 6].

For all these districts a four wire three phase system from "Y" wound armatures supplied with the fourth terminal is used, the generator delivering a maximum of 4,150 volts, with 2,400 volts between the neutral point and any one of the outside terminals. There is thus available a voltage best suited for the single-phase lines in the immediate locality and the higher voltage for four wire three-phase transmission to centers in more distant localities.

In the Northern District there have been installed in the original generating station shown on the map, motor generator sets,

FIG. 6. Scale [illegible]

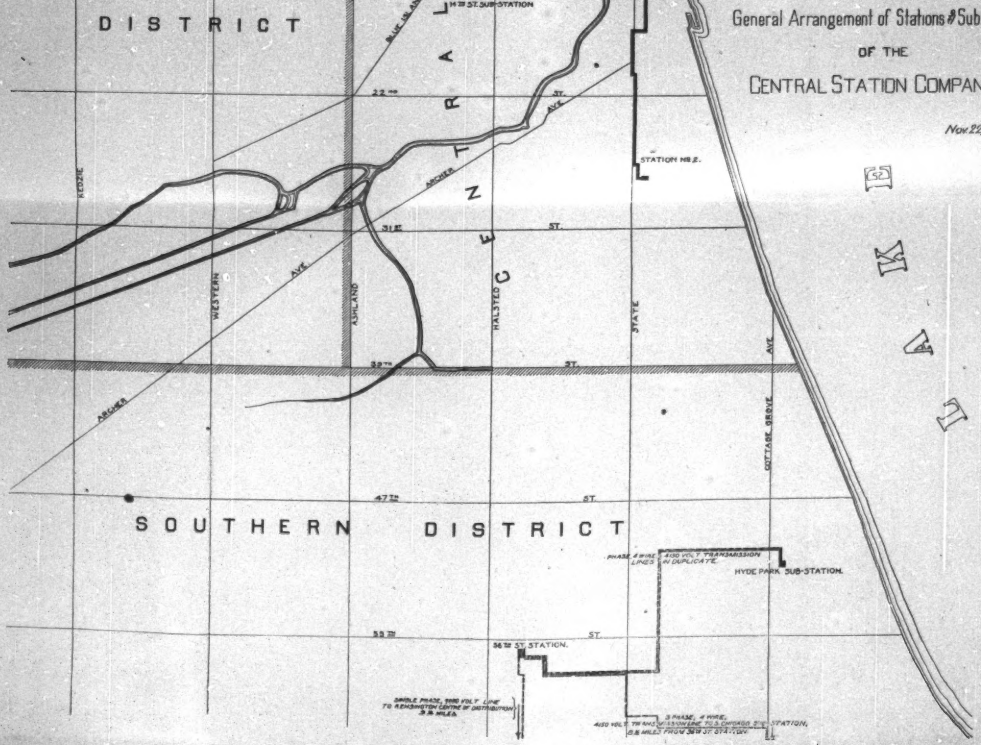

FIG. 6.—Scale 1 inch = 1 mile.

General Arrangement of Stations & Sub-stations

the motor side of which are fed by 25-cycle three-phase current at 9,000 volts from the principal generating station at Harrison Street, the generating side of the set being a three-phase "Y" wound machine delivering 4,150 volts across its outsides, and 2,400 volts between the neutral and any outside terminal. It is the intention of the company to ultimately shut down the steam generating plant in this district and supply all the energy by motor generator sets similar to those now in operation.

Several years ago an extension was made from the Northern District power station to Edgewater, a suburb lying four miles north of this station, for the purpose of taking over the business in Edgewater, which was then supplied by a three-wire direct current local plant. The conversion was accomplished by installing in the small generating station at Edgewater, two large transformers with three-wire secondaries, which were connected directly to the bus bars of the station after shutting down the direct current generators. The primaries of these transformers were fed by a 5,000-volt line from the Northern District station, customers in Edgewater then receiving alternating current over three-wire network with results which have been more satisfactory than when the local plant was operated. The regulation of the line is effected by means of induction regulators in the Northern District station.

In the Western District where the four-wire three-phase system is likewise employed, the sub-station is located as shown on the map, and current is furnished to the circuits emanating from this sub-station by means of motor generator sets, the motor sides of which receive three-phase current at 9,000 volts from the principal generating station at Harrison Street.

In the Southern District there has been erected a principal generating station, the location of which is shown on the map as Fifty-sixth street, and the territory supplied is 35 square miles. This station supplanted six generating stations formerly operated by as many different companies. The system now employed in this district is also a four-wire three-phase system, single-phase mains provided with potential regulators being used for distribution in the Englewood district, which territory adjoins this station. Four-wire three-phase lines transmit at present about one-half the output of the generating station 3½ miles to Hyde Park, where a distributing sub-station is established. The first story of the building is the sub-station proper, while the second story is fitted up as an apartment for the man in charge of the sub-station. On

the first floor there is also an office and storeroom, where lamps and small operating supplies are kept on hand, the trouble man for Hyde Park reporting at this station.

The sub-station proper consists merely of a switchboard and potential regulators, which are installed on each circuit, no step-down transformers being necessary. Each circuit is equipped with a single-pole three-throw oil-balancing switch, by which the single-phase circuits are balanced on the three phase bus bars. From Fifty-sixth street station a transmission line also runs 8¼ miles to South Chicago, where another local center for distribution is established.

The system of distribution in these outlying districts is such that series alternating arc lights may be operated when desired from the bus bars of the generating station or sub-station.

The method of generating low frequency alternating current in one or two large stations and transmitting the energy at high voltage to sub-stations for conversion to direct current in thickly settled districts is now being adopted in some of the large and more progressive cities of Europe, notably in Berlin and Milan.

The general scheme of generation and distribution in Berlin is similar to the system in use in the central district of Chicago, with the exception that in Berlin, motor generators are used instead of rotary converters. Their practice also differs from the American in that the direct current network is not interconnected, as for some reason they consider it dangerous to do so.

In addition to the former direct current stations in the central district of Berlin, they have erected two large stations away from the center of the city, each having an ultimate capacity of about 40,000-horse power. In these plants three-phase current is generated at 6,000 volts by direct coupled three-phase units, and is transmitted to the various sub-stations throughout the city. One of these sub-stations has at present a capacity of 7,000 K. W., current being taken in at 6,000 volts and reduced by means of three part transformers of 1,000 K. W. each to the proper working pressure for operating motor generators of about the same capacity. The generating side of each is wound for 250 volts. It is the practice of the Berlin company to use storage batteries in connection with their sub-stations in much the same manner as is being done in American sub-stations.

The general scheme of transmission and distribution in the City of Milan involves the use of three-wire direct current distri-

bution in the central portion of the city, supplied by a motor generator station located near the Cathedral, with a 3,600-volt three-phase primary distribution for the territory beyond the central district. Current is generated at 13,500 volts with a frequency of 42 cycles per second by three-phase alternators in the water-power plant located at Paderno, 32 kilometres from the steam station at Porta Volta. At the latter point the voltage is reduced to 3,600 volts by step-down transformers and connections made in parallel with the 3,600-volt generators in the steam station at Porta Volta. From this 3,600-volt bus, current is distributed throughout the outlying portions of the city by means of primary mains which feed transformer houses located at convenient points. From these transformer houses small secondary networks are built to supply the customers in the neighborhood.

The sub-station near the Cathedral receives its current at 3,600 volts from the main bus bar in the station at Porta Volta, the motor side of the generators in the sub-station being wound for 3,600 volts.

The Milan Edison Company operates the street cars of the City of Milan as well as doing the lighting and power work for the city, motor generators in the sub-stations being also used for operating the street cars.

Storage batteries are used in Milan for both railway and lighting business, the railway battery having a capacity to take care of the maximum load of the railway for one hour, and the lighting batteries being sufficient to take care of the full direct current lighting load at the time of peak.

The general principles and systems which have been here advocated as advisable for Chicago should be applicable to any large American city as the general conditions in all large cities are approximately the same. This, however, may not necessarily be true in the case of the smaller city or town as they are usually affected by some local conditions, and in some instances even the general conditions may not be such as to make the same system applicable.

The aim of every central station manager should be to strive for simplicity and interchangeability in his system of generation and distribution, avoiding as far as possible multiplicity and complexity of methods, building up a distribution system which shall be universal, thus standardizing the customers' appliances and apparatus throughout the city.

A paper read at the 158th Meeting of the American Institute of Electrical Engineers, New York and Chicago, November 22, 1901.

[ADVANCE COPY—SUBJECT TO REVISION.]

LOCATING FAULTS IN UNDERGROUND DISTRIBUTION SYSTEMS.

BY HENRY G. STOTT.

With the rapid and extensive growth of underground cable systems for the distribution of electricity for light and power purposes a problem of great practical importance has arisen, namely, to find a method of quickly and accurately locating a fault or ground in any part of the system.

With small conductors, such as those used for telegraph cable, the ordinary Blavier and loop tests with galvanometer, Wheatstone bridge and battery suffice; but the percentage of error in locating a fault varies directly with the cross section of the conductor or inversely as the resistance. Any one familiar with the most refined methods of battery test will admit that the loop test is the best of all, as it eliminates the worst variable, namely, the fault resistance. Even under the best conditions the loop test has an element of uncertainty in the variation of the zero on the galvanometer due to earth currents getting into the cable through the fault. In a city, the source of this error becomes of greater importance than in submarine cables, owing to the leakage of street railroad currents through the earth from the rails. As a matter of fact, it is frequently impossible to use a sensitive galvanometer on any test involving the use of the earth as a part of the circuit.

Loop tests carried out with the comparatively large current of ten amperes, using millivoltmeters instead of reflecting galvanometers in the hope that the stray currents would thus become such a small percentage of the test current that the

errors due to the presence of the former would be practically eliminated, also failed entirely, and the conclusion was reluctantly reached that the galvanometer and battery must be abandoned whenever the resistance to be determined was less than .25 ohm.

The distance between manholes is evidently the practical degree of accuracy essential to any successful method. This will average about 350 feet. Assuming that .25 ohm is the limit of accuracy obtainable under these conditions, in the loop test this means that the method is not applicable to any conductor larger than No. 9 B. & S. gauge, and therefore of no practical value for lighting and power purposes.

Resistance measurements having been eliminated as a possible means of solution, there remain three others, which may be called:

(*a*) "The cut-and-try method."
(*b*) "The smoke method."
(*c*) "The compass method."

(*a*) The "cut-and-try method" is too well known and too bad to merit much description, as it simply means cutting the cable into as many sections as necessary until the fault is finally located in a length between manholes. This is a slow, expensive and unscientific method, and should only be used as a last resort. A three-conductor high-tension cable joint costs from five to ten dollars, and a jointer and helper cannot make more than two per day, so that if the cable is five or six miles long it may easily take four or five days to get the cable in service after removal of a fault.

(*b*) The "smoke method" is also crude, and simply consists of putting a current of sufficient magnitude into the cable through the fault, to cause the insulation to burn and give out volumes of smoke, by means of which the location of the burnt section may be discovered upon opening up the manholes.

The method is more rapid in yielding results than (*a*), as no unnecessary cuts are made in the cable, but it may give rise to serious trouble in other cables, especially if the fault be in or near a manhole, as the flames may burn not only a great length of the cable itself, but also other cables, or cause explosions due to the ignition of the gases ever present in all city conduits.

(*c*) The "compass method" is, in the writer's opinion, the only practical and safe means of quickly and accurately locating a

ground in cables larger than No. 9 B. & S. gauge. This method consists, briefly, in sending a constant continuous current of about 10 amperes into the cable through the ground, the current first passing into an automatic reverser, which reverses the direction of the current flow every 10 seconds. A manhole is then opened near the center of the cable length and a pocket compass laid on the lead sheathing of the faulty cable and observed for say half a minute. If the ground is further from the source of reversed current, the compass needle will swing around approximately 180° upon every reversal at the end of each 10 seconds interval. The manhole is immediately closed and another opened, say a mile further away from the source of test current, and if no motion of the compass needle occurs, then the fault has been passed and another manhole is opened between the two first positions, and so on until the fault is finally located in a section between two manholes.

It will be observed that by this method (1st) the cable is not cut, thus causing no delay or expense in rejointing; (2d) the number of manholes opened is a minimum, and the time spent in each is only about one minute; (3d) the amount of current used is so small that no arcing or burning occurs and no explosions.

Figure 1 shows one form of reverser used by the Manhattan Railway Company, consisting of a ½-H. P. three-phase induction motor, geared to a two-part commutator, which revolves in oil in order to ensure the quick reversal of current without danger of arcing across between segments. An ordinary constant continuous current arc light machine is the most convenient source of current for this test, as it will supply a constant current throughout a wide range of voltage, thus automatically adjusting itself to the varying fault resistance. Should an arc light machine not be at hand, 500-volt current can be used through a resistance and reverser.

Before putting on the reversed current it is advisable to break down the fault resistance by the application of a high potential testing transformer to the cable for a few seconds.

This method of test is especially useful in any network of cables, such as 2,200-volt single, two or three-phase mains and feeders, as the test current can be run on the network, without shutting down the supply service or interfering with it in any way, by simply sending the 10-ampere reversed current through

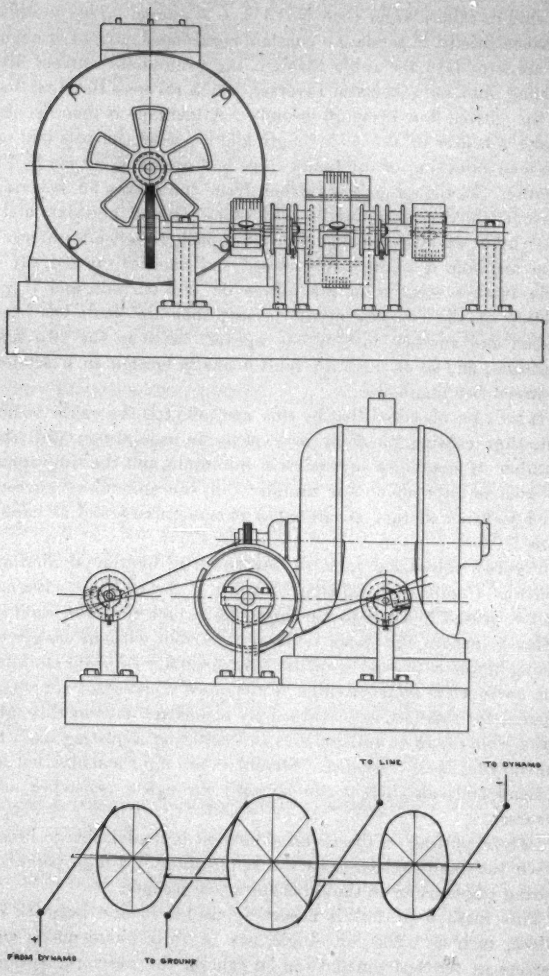

FIG. 1.—Motor Driven Current Reverser.

a reactive coil (or the primary of a transformer) before entering the grounded main. This is merely done to protect the arc light generator in case another ground should develop and thus cause a short-circuit on the A. C. generator. This method of testing live circuits is only applicable, of course, to those supplying alternating current and having no permanent ground attached.

After using this method of locating faults for four years, the writer cannot recall any case, in which the method was properly applied, that required more than three hours to locate a fault in cables having a length of from four to six miles. The whole secret of this rapidity lies in the fact that the first test at the center of the line eliminates one-half of the cable from the question. To find a fault in a duct between manholes in a similar length of cable, by any other method known to the writer, may easily take two days, and as many more may be required to repair the cuts.

The writer trusts that the above notes may be of some practical value to the profession, and that the method recommended will be found as certain and satisfactory by those who have not as yet used it as by those who have.

New York, November 8, 1901.

A paper read at the 158th Meeting of the American Institute of Electrical Engineers, New York and Chicago, November 22 1901

[ADVANCE COPY—SUBJECT TO REVISION.]

THE BUFFALO HIGH-TENSION CABLE DISTRIBUTION SYSTEM.

BY HAROLD W. BUCK.

In the development of the electrical transmission of power many propositions are being presented of a water power or coal mine situated within such a distance of a city that it is cheaper to transmit power from the mine or waterfall than to generate it by steam in the city itself. In such systems three engineering elements must be considered: first, the generating plant; second, the transmission line, and third, the method for distributing the power at the end of the transmission line. Electrical generating plants and transmission lines have been the subject of many discussions, but the terminal arrangements for transmission lines are newer in their development, and it is the object of this paper to bring the matter up before the members of the INSTITUTE for discussion, the problem presented being the best method of distributing the power throughout a city after a point has been reached on the transmission line where it is no longer safe to carry the power overhead at the transmission voltage. Such limitations exist on the outskirts of all cities.

In order to serve as a basis for discussion and to point out the various considerations which enter, a brief description will be given of the method which has been adopted for the distribution of Niagara power in Buffalo.

Fig. 1 shows a map of the Niagara–Buffalo transmission line indicating the relations between the overhead circuit and the circuits of distribution within the Buffalo city limits, the numeral 3 on the map indicating the terminus of the 22,000-volt overhead

three-phase lines. At this point the three overhead circuits, each having a capacity of 10,000 H. P. at 7 per cent. line loss, enter a terminal house, and are connected, as shown in Fig. 2, through circuit breakers, selector switches, bus bars, etc., to the 22,000-volt primaries of the step-down transformers. These transformers have a capacity of 3,000 H. P. each, and are of the oil-water cooled type. The secondaries of the transformers are wound for 11,000 volts, making the ratio of reduction of voltage 2:1. The secondaries of the transformers are connected through selector switches and two sets of bus bars to the underground cables, each of which is connected through an air-break circuit-breaker. With the arrangement shown, the Buffalo system can be operated in two sections if desired, and any overhead circuit or any cable con-

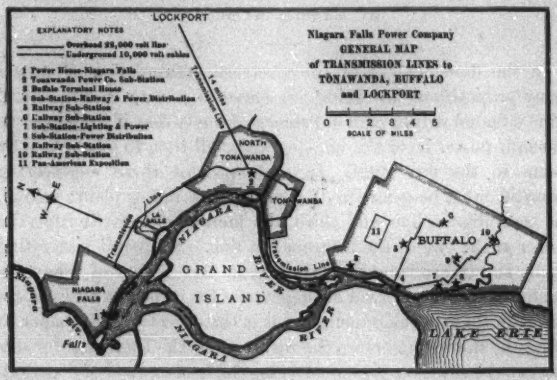

FIG. 1.

nected to either of the banks of transformers. The 11,000-volt cables supplied from the secondaries of the terminal house transformers are drawn through tile ducts under the streets in the usual manner, and carry the power to the various sub-stations throughout the city of Buffalo. At present there are five feeders, each consisting of No. 000 triple-conductor lead-covered cables. Two of these have 9/32″ rubber, two 8/32″ rubber and one $6\frac{1}{2}$/32″ paper and 4/32″ paper over-all. The lead in all cases is $\frac{1}{8}$″ thick.

Fig. 3 shows the general arrangement of cables throughout the city, with the various methods which are used for transferring

from one to another and for cutting out damaged sections of a cable by means of section switches, so that the entire length of cable from the terminal house will not have to be cut out of service. Special attention is called to these section switches, which are shown in Fig. 4. They are of the triple-pole, single-throw type of oil-break switch, with a waterproof hood of iron bolted to the top of the switch frame for the protection of cable heads and leads. These switches are installed in vaults under the city streets, placed at convenient intervals. Some of the vaults are as large as 10′ x 12′. The switches are absolutely waterproof

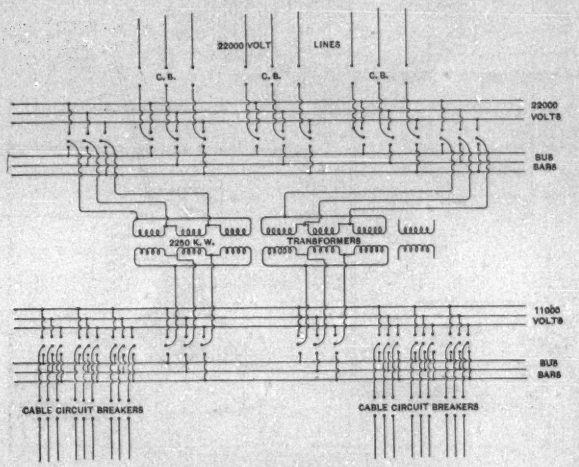

FIG. 2.—Connections Buffalo Terminal House.

and could be submerged if necessary without danger, and will open the circuits under heavy loads without difficulty. They have proved of great convenience at times when repairs have been necessary on sections of the cables, and for locating faults without the necessity of cutting the cable. I believe that underground section switches of this kind would prove of great service to all high-tension cable systems, and believe that the design shown is entirely safe for service at 11,000 volts.

In all, seven sub-stations are supplied with power at 11,000 volts, three-phase, distributed as follows with reference to Fig. 3:

Station No. 4.—2,000 H. P., for railway purposes, transformed from 11,000 volts to 360 volts and fed to four 500 H. P. rotary converters. 1,000 H. P., for general power distribution on a tertiary system at 2,200 volts, three-phase, the voltage being lowered from 11,000 volts by three 250 K. W. transformers. This 2,200-volt distribution is partly overhead and partly underground.

Station No. 5.—1,500 H. P., for railway purposes, transformed from 11,000 volts to 360 volts and fed to three 500 H. P. rotary converters.

Station No. 6.—1,000 H. P., for railway service, as in Station No. 5.

Station No. 7.—5,000 H. P. is transformed from 11,000 volts to 360 volts and fed to the plant of the Buffalo Lighting Company in an adjacent building. 1,000 H. P., transformed to 2,200 volts, three-phase, for general power distribution on the tertiary system.

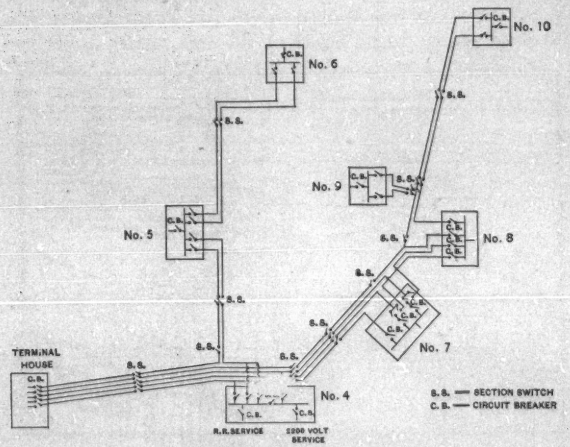

FIG. 3.—Buffalo 11,000-Volt Cable System.

Station No. 8.—2,000 H. P., transformed from 11,000 volts to 2,200 volts, three-phase, for power distribution on the tertiary system.

Station No. 9.—1,500 H. P., transformed from 11,000 volts to 360 volts, for supplying power to three 500 H. P. rotary converters for railway purposes.

Station No. 10.—1,000 H. P., for railway purposes, as in Station No. 9.

It might be asked why the power is not transmitted from Niagara Falls at 11,000 volts and distributed through the underground cables without transformation. It will be found, however, that the saving in copper on the transmission lines by the use of 22,000 volts more than pays for the transformer installa-

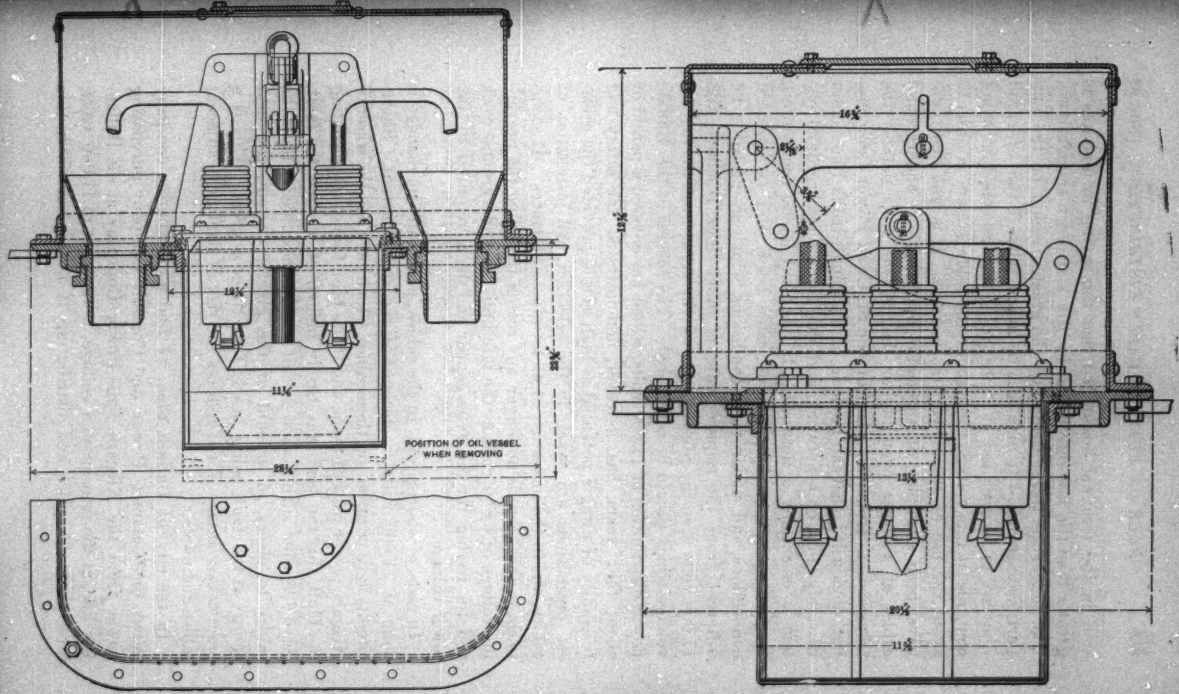

Fig. 4.—Underground Switch.

tion in the terminal house, and that the saving in line loss is greater than the loss introduced by the step-down transformers. The longer the transmission line the greater would be the proportionate saving. It may also be asked why, if the overhead lines are to be operated at 22,000 volts, the transmission cannot continue at this voltage throughout the cable system in order to avoid the use of step down transformers. It is true that there have been examples of successful operation of underground cables at voltages even higher than 22,000 volts, notably the transmission from the plant of the St. Croix Power Company, but, obviously, what can be done on a through trunk line cannot be safely done on a network, and the Buffalo underground system is essentially a network. It has many lateral connections, frequent joints, section switches, cable heads and switchboard connections, and under these conditions, which are probably no different from the requirements of other cities, I believe that 11,000 volts is, in the present state of the art at least, the highest voltage which should be considered. The success of the Buffalo power distribution at 11,000 volts, which has covered a period of about four years, has, however, demonstrated the safety and feasibility of using a potential as high as this, provided the greatest precautions are taken in the selection and installation of cables, and in the insulation of all terminal appliances. It seems to show that there is no longer any reason for fixing the prevailing voltage of 6,600 volts as the safe limit for underground work and for paying for the extra copper and ducts required by the lower voltage.

In cases of short-circuit in the cables, practically no damage is done at 11,000 volts on account of the small current. Short-circuits have occurred on these cables, which have had the whole of Niagara power back of them, and it has been found, after locating the fault, that the lead was barely melted off around the fault. At 6,600 volts such a short-circuit would undoubtedly blow the cables to pieces, on account of the greater current, the heat energy at the fault being nearly four times as great. This is a practical advantage, for it reduces the risk of damage to adjacent cables and ducts.

In the city of Buffalo, then, we find a distributing company called the Cataract Power and Conduit Company purchasing power from the Niagara Falls Power Company at the Buffalo city line, at the transmission voltage, lowering it to 11,000 volts, three-phase, 25-cycles, and distributing it as raw material in this

form as dealers in power. To the railway company it is delivered for transformation and conversion for use on their own direct current circuits, to the lighting company for conversion into the various forms in which they re-distribute it to small consumers, and it is also delivered to various factories using power in quantities from 75 H. P. and upwards, to which consumers power is supplied from the tertiary system mentioned at 2,200 volts, three-phase, from sub-stations owned and operated by the Cataract Power and Conduit Company.

From a business as well as an engineering standpoint it is believed that the methods used in Buffalo as described are very satisfactory and economical. The primary company, viz., the Niagara Falls Power Company, confines its attention to the generating plant and transmission line, the distributing company to the delivery of three-phase 25-cycle alternating current power, and the railway and lighting companies to the interests of their own circuits. This separation of responsibilities is entirely logical and most convenient. It would be still better if the Cataract Power and Conduit Company could confine itself to the delivery of power at a single voltage, viz., 11,000 volts, but the tertiary distributing system at 2,200 volts is necessary, for the reason that it is obviously not safe to supply small consumers of power, such as small factories, with connections at so high a voltage. By transformation to 2,200 volts the numerous "grounds" which occur on these circuits are made independent of the main cable system, and the introduction of the transformers adds to the self-induction of these circuits and limits the violence of short-circuits which occur upon them.

The transformation of voltage at the city line from 22,000 volts to 11,000 volts, beside being necessary, is also a positive engineering advantage, for the reason that it renders the 11,000-volt cable system independent of "grounds," and high voltage disturbances from lightning, resonance, etc., which occur at times on the transmission line, since there is no electrical connection between the two. Although there have been several instances of rises of potentials on the overhead line far above the normal, resulting probably from resonance, no rises of voltage have been noted as having been transmitted to the cables by induction through the cores of the step-down transformers.

It is believed that the methods here described are practicable and convenient, and can be safely followed in principle by those who are planning similar systems of distribution.

A paper read at the 158th Meeting of the American Institute of Electrical Engineers, New York and Chicago, November 22, 1901.

[ADVANCE COPY SUBJECT TO REVISION.]

ALTERNATING CURRENT AS A FACTOR IN GENERAL DISTRIBUTION FOR LIGHT AND POWER.

BY CHARLES F. SCOTT.

The foregoing title immediately suggests the old-time controversy, alternating *versus* direct current. The present problem, however, may be more accurately stated, alternating current only *versus* alternating current and direct current.

The economical radius of direct current supply from a central station is so limited that even in a strictly direct current system, if it covers considerable area, recent engineering prescribes a large alternating current generating plant furnishing power to rotary converter sub-stations, and from these the direct current is distributed. This is witnessed in recent installations in Greater New York.

The problem therefore is this. For general distribution for lighting and power service where the current is generated in alternators is it desirable to utilize the current as alternating current or to convert it into direct current?

Before taking up in detail the various elements involved, the following statements may in general be considered as axiomatic.

(1) Simplicity demands a uniform system with elements as few as possible and requiring a minimum of attention. Converting apparatus requires rotating machinery and the presence of attendants, and these involve first cost, operating expense, complication and liability to interruption of service.

(2) In classes of service for which direct current possesses no advantage over alternating current conversion is undesirable. For

example, the simplest case is incandescent lighting. It is doubtful whether any one would propose converting to direct current if incandescent lighting alone is to be supplied.

(3) In outlying districts or other territory where the output from a sub-station would be quite small, it would obviously not be economical to convert into direct current as many of the expenses of such a sub-station would be relatively large, so that the cost per kilowatt for converting into direct current would be excessive.

These conditions limit the general problem, and the question may now be stated thus: In those cases in which the conversion from alternating into direct current is commercially practicable, is it necessary or desirable?

It will be readily granted that usually a large part of the service would be as satisfactory if operated by alternating as by direct current. With regard, then, to those elements in which there is a difference of opinion, are the reasons for the use of direct current sufficient to justify the increased complications and expense of the converting apparatus?

To answer this intelligently we will consider it in two divisions;

(a) In the utilization of electric energy what advantages has direct current over alternating current?

(b) When energy is generated as alternating current what disadvantages are involved in utilizing it as direct current?

Taking up the first of these let us consider the ordinary classes of service and the means of providing for them.

Incandescent lighting may be considered as indifferent to the character of the current whether it is alternating or direct, provided the frequency be sufficiently high to prevent flickering.

Arc lighting is most extensively carried on by the enclosed arc lamp which is satisfactorily operated from direct current circuits, and also from 60-cycle alternating circuits, so that there is no compelling reason for choosing either one current or the other as far as arc lamps are concerned.

The Nernst lamp which is quite satisfactory in its operation on alternating current but not on direct current, gives a positive reason for choosing the former.

In discussing motor service it is not the intention here to enter into a controversy as to the relative merits of alternating and

direct current motors. Suffice it to say that both are in extensive use for nearly every kind of service. The induction motor is notable in having no commutator, and on account of its ability to stand various kinds of abuse. It is especially fitted for general distribution of power in all sorts of places as such motors receive little or no attention.

For constant speed work probably no one will question the superiority of the alternating current motor from the standpoint of the man who uses the motor and pays for rapairs. Any objections which may be brought forward will probably be urged on account of reasons applying to the supply system such as power factor, starting current and voltage regulation. These items may be provided for by properly designing the system, and they cannot be regarded as legitimate objections to the use of the alternating current motor.

For variable speed work the conditions are different; the fundamental difference is due to the fact that although there is a close correspondence between the performance of the induction motor and the direct current shunt motor with constant field excitation the alternating current motor does not have an exact analogue to the direct current series motor. It follows that induction motors cannot exactly duplicate all direct current motors. Therefore the results which may be desired must often be obtained in a different way from the methods employed with direct current motors.

From the above summary it appears that all of the important classes of service for which current from a central station is used may be successfully undertaken either by the direct current or by the alternating current, sometimes equally well, sometimes with the advantage on one side and sometimes with the advantage on the other side. The most important difference is probably in the case of variable speed motors and the importance of this will depend quite largely on the proportion of this kind of service. Although the alternating current motor cannot exactly replace the direct current motor, so that there may be some inconvenience in changing from one system to the other, yet when a new plant is being laid out, it is probable that the cases are very rare in which it would not on the whole be practicable to utilize either alternating current motors or direct current motors.

To consider next the apparatus employed for producing and distributing current, the elements in the two systems may be set forth as follows:

ALTERNATING CURRENT ONLY.	ALTERNATING AND DIRECT CURRENT.
Alternators,	Alternators
Switchboards,	Switchboards,
Primary Mains,	Primary Mains,
Transformers,	Sub-stations with
Distributing Circuits,	Switchboards,
	Transformers,
	Switchboards,
	Rotary Converters,
	Switchboards,
	Distributing Circuits,

Comparing these in detail, the generating station in general will be substantially the same for the two systems, although a higher frequency will usually be employed if there is little or no conversion to direct current.

The primary feeding system will also be substantially the same in the two cases, differing, however, in the number of points at which the transformation is made to the low voltage, and the distributing system is supplied with current.

The sub-stations for conversion into direct current constitute the great difference between the two systems. Sub stations with converting apparatus are expensive to install and to operate. The cost of the sub-station naturally makes it desirable to have as few as possible, hence they are located at as great a distance apart as the distributing circuits will permit.

The cost of distributing circuits for direct current is therefore very much greater than for the low tension alternating current circuits to which current is supplied from a large number of transforming points since the alternating current circuits are comparatively short, and the cost of copper is hence greatly reduced. This effects a saving not only in the cost of the conductors themselves but also in subways and ducts, which are often limited in capacity, and high in cost.

The liability to accident and interruption to service is inevitably greater in the system which converts to direct current than in that which merely transforms to a lower voltage since the sub station with its switchboards and rotating machinery intervenes between the generator and the consumer.

The storage battery is an element which is sometimes presented as a reason for adopting direct current, as it may be readily added to the system. It may, however, be used in connection with alternating current distribution. A rotary converter may be employed

for charging the storage battery, and in turn the battery can supply current through the converter to the alternating circuits. In this manner the battery may be related to the alternating system in substantially the same way that it is usually related to the direct current system except that the converter is between the battery and the service.

The foregoing general comparison between the two generating and distributing systems evidently favors the one which employs alternating current only. The introduction of converting apparatus therefore must be justified by advantages accruing in connection with the utilization of the current which are sufficiently great to overbalance the extra cost and complication.

To change an existing direct current system into an alternating curent system is in many cases a difficult matter. The circuits which are suitable for direct current may not be suited for alternating current. The motors used for the direct current would of course be useless on the alternating circuits. These and other similar points complicate the general problem, and when an existing direct current plant is to form part of a large system, such considerations often determine the plan to be followed.

The foregoing discussion applies particularly to large city plants for supplying lights and stationary motors for general work, and it has been assumed that the entire service is supplied either by direct current or by alternating current. There are, however, some cases where a combined service is advantageous, alternating current being supplied for certain districts, and direct current for others.

In cities, a combined service for general distribution is sometimes applicable for furnishing direct current from sub-stations to districts which have previously been supplied by direct current generating plants, while alternating current is furnished to the outlying parts. The same generators may be used for both classes of service, and may supply them simultaneously. Quite similar results may be attained from a direct current generating plant, the alternating current being obtained from inverted rotary converters.

In smaller towns a combined service from an alternating current plant is often used for supplying railways by 60-cycle rotary converters in connection with general lighting and power, the latter service being entirely by alternating current. In many

cases the lighting and railway work can be operated from the same bus bars, as the automatic compounding of the rotary converters is such as to make the voltage upon the general system sufficiently constant for lighting service.

Probably the most pertinent conclusion to be drawn from a discussion of this kind is that there is no ideal system, and no panacea plan which can be universally applied. Existing and local conditions, special requirements and the relative importance of the various classes of service to be rendered must all be taken into account in determining what will be adequate in an individual case.

The systems which we have been discussing have an important and far-reaching influence upon industrial life and social activity aside from their engineering aspects. It would be difficult to find an agent more instrumental in bringing about the unification and concentration of diversified industries and interests than electric energy in the form of alternating current.

The recent electrical development in Greater New York demonstrates this on a magnificent scale. A generation ago it would have defied the imagination to discover any natural connection between such widely different agents as horses pulling street cars, locomotives drawing elevated trains, gas lighting houses and streets, water operating elevators, stoves heating and cooking, and engines of every sort and class doing a hundred kinds of work. But all of these and many others are in common being superseded by the electric current, which does not merely replace but develops, expands and transforms. It is notable that all of this varied service is to be supplied from alternating current generators; also that the outcome of the evolution of plans for general distribution and for railway work is identical in that alternators of the same frequency are being installed for both, so all could supply current to a common universal system.

A paper read at the 158th Meeting of the American Institute of Electrical Engineers, New York and Chicago, November 22, 1901.

[ADVANCE COPY—SUBJECT TO REVISION.]

NOTES ON THE ALTERNATING CURRENT SYSTEM OF DISTRIBUTION.

BY W. S. BARSTOW.

Distributing systems are usually referred to under two headings—direct and alternating.

The direct current distributing system, starting in the early '80's and appearing generally in its three-wire form, is what may be termed a universal system, since from the same conductors, and without any modification whatever at the customer's service, current is furnished direct to any electrical apparatus, whether for supply of power, light or heat.

The alternating current distributing system, making its appearance in its single-phase form about the same time as the direct, never started as a means of universal supply, being confined in its earliest stages of development to the furnishing of energy for light and heat only. To the absence of the alternating current motor can probably be traced its restricted use and the early slow progress in this form of current supply. Had there been early developed a single-phase motor which would have met all the conditions of a direct current motor in construction, economy and cost, then there is no doubt but what the three-wire, single-phase alternating current system would have come rapidly to the front. As to whether it would take the place at the present time of large installations of direct current supply, might perhaps be doubtful, since the storage battery as a part of the general system is gaining ground and rapidly becoming indispensable.

The alternating current distributing system was first exploited as a house-to-house supply, and continued as such until within

recent years, when efforts were made to interconnect the secondaries to increase the efficiency and reliability of the system. It was soon found, however, that the paralleling of transformers in old systems already erected, through small secondary mains, was much like paralleling compound generators through a small equalizing bus, and many failures were the result. Steps were then taken to install mains of such a size as to make the drop or loss between two transformers negligible, and for a short time many plants operated succcessfully with transformers in multiple on fairly long secondary mains. As the demand for current on the mains increased, however, the change in the size of conductors was not followed up, and the old trouble returned. The system to-day, therefore, has almost reverted to a house-to-house supply, although the transformers are arranged in groups, connected to secondary mains, and providing, in case of accident, for interconnection.

The only practical and successful method of paralleling transformers on secondary mains of distribution is the placing of each transformer or bank of transformers on a separate feeder and providing at the station means for regulation on such feeder, so as to make it possible to divide up the load on the different transformers and compensate for any difference in transformer regulation. Such a system is in successful operation in several large plants, and is productive of good results. When the alternating current system is permanently standardized the transformer will no doubt be considered a part of the feeder, only one transformer or bank of transformers being installed at a single distributing point of a single feeder.

As before mentioned, owing to the early absence of any commercial single-phase motor, there was no incentive to standardize and develop the alternating system, as has been done in the case of the direct, and it was not until the last few years that the alternating system, by the abandonment of the single-phase and the change to multiphase, approached anything like a universal system of supply. Up to the time of the appearance of the multiphase motor the development of motor business on alternating systems was very restricted, as the uses to which the single-phase motor could be put were more or less limited. On the other hand, the introduction of the multiphase motor necessitated a change in the entire syystem of distribution, and it is not until the last few years that single-phase has entirely given place to

multiphase systems, not, in fact, until it became apparent that the multiphase motor, under any stage of development, would prove superior to the single-phase. Probably the simplest multiphase alternating current distributing system which would be first thought of would be the two-phase, three-wire primary and three-wire secondary. Such a system might be satisfactory where light only is used and where the middle wire of the secondary system is always kept of proper size to maintain the balance, but there is no doubt that the better commercial form is the four-wire secondary, or in fact, the two phases taken directly from the machine to the customer's service. With the same number of conductors, a further saving of copper is secured by the use of the four-wire, three-phase. With either of these systems, where transformers are a part of the individual feeder, a complete interconnection of mains can be secured. When the supply from these secondary mains is introduced into the premises of the customer, necessity for installation of additional transforming apparatus arises. If the secondary be of a pressure of 110 volts between phases, either large motors must be installed at this pressure or step-up transformers used. In either case the mains must be very large to take care of this low pressure motor current, and especially when such multiphase motors are frequently stopped and started. If the secondary be of a pressure of 220 volts, the size of conductors can of course be reduced, but it is still necessary to install a transformer or balancing device if 110-volt arc or incandescent lamps are used.

With the object of simplifying the system, in many cases the multiple network of secondary mains has been omitted, and in their place a multiple network of primary mains substituted, the transformers being located on the premises of the customers. This reduces the system to a house-to-house supply and makes necessary the building of vaults or in other ways satisfying the insurance companies, as the full pressure is introduced into the premises of the customer. Such an arrangement necessitates an increase in the transformer capacity of the system, since the capacity of the transformers must be nearer the capacity of the connected load, whereas if grouped and the supply furnished through secondary mains, the transformer capacity can approach nearer the actual maximum load of the system.

In order to reduce the fluctuations of pressure in the lighting circuit, caused by large direct-connected alternating current mo-

tors stopping and starting, there have been devised several systems which provide separate means of supply for motors and for lights, by providing additional "power" conductors, but in nearly all cases such systems necessitate the installation of primary transformers on the premises of the customer. With a view of furnishing a single service to the customer without installing apparatus on the premises, there are one or two systems employing four or five low-tension conductors in the secondary, from which different combinations of pressure are secured for the separate operation of motors and lights, but such systems have not been put to extended central station use.

But if the alternating system has not yet attained the standard of a large distributing system for compact territory, it is nevertheless alone in its field of transmission and house-to-house supply in scattered territory, and yet even in these fields too much attention cannot be paid to the consideration of future permanent supply, there being many cases of its having been used as a very temporary means of "getting there." A generator is bought, a few miles of small-sized conductors erected, enough transformer capacity installed to supply the present wants, and the installation is complete and trouble begins. When extra transformers are required, they are purchased one by one in small sizes and connected to feeders already too small to carry the load. The idea of a change in the size of conductors never occurs, and soon the station manager does not think much of the alternating system, and by that time the public generally agrees with him. This state of conditions is due to the fact that the system has not been designed with an idea of permanency, and the future and uncalculated demand upon it completely destroys its usefulness. Such a state of affairs existed in the pioneer days of direct current engineering, the future demands seldom receiving the consideration which they warranted. Inspectors "determined" the system and visited every corner of the city, every private house, hotel, etc., and finally "determined" that the heaviest direct current mains in the business section should be 27,000 c. m. and the feeder 41,000 c. m. Three years later, in the same city, these mains were replaced by others of eight times the capacity, and were even then too small. Such was true of the simple direct current system, and it was even more true of the alternating system. The idea that the alternating high-pressure system saves copper, and that therefore it may be possible to save it all, has often brought about a final failure of a promising success.

What is required to-day, however, if the alternating current, besides retaining its field of transmission and scattered distribution where it is supreme, would enter the compact direct-current field of distribution, is:

First.—A standard type of motor, which can be used for all classes of business demand and will meet the same commercial requirements as the present direct-current motor.

Second.—A universal system of supply, which does not require transformers, etc., or anything outside of the meter itself, to be located on the premises of the customers.

Third.—Some apparatus which, in connection with alternating current, will take the place of the storage battery supply on the direct current.

With these requirements complied with, the alternating current distributing systems can expect to take the place of many of the large direct-current systems, not only for the supplying of light, heat and power, but also for transportation.

November 12, 1901.

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[ADVANCE COPY, SUBJECT TO REVISION.]

THE DISTRIBUTION BY THE THREE-PHASE SYSTEM AND THE OPERATION OF SINGLE-PHASE CIRCUITS BY IT.

BY W. L. R. EMMET.

Since the single-phase alternating distribution preceded the use of polyphase currents, there has naturally been a tendency to continue its use, and a full appreciation of the advantages of polyphase currents has not been acquired by many of the practical men who handle distribution problems. The first uses of polyphase currents were for power alone, the old single-phase lighting systems being unchanged. As time has gone, however, the use of single-phase apparatus has steadily diminished, and the production of polyphase apparatus has increased; and although there is still some demand for single-phase generators, an investigation will show that the best informed electrical engineers have now discarded them altogether.

An extensive experience with a single-phase, two-phase, three-phase and other apparatus, has led me to believe that for almost all purposes of lighting and power distribution the three-phase winding is the most desirable for central station generators, and that two-phase and single-phase windings have, in the great majority of cases, no good reason for existence.

It is not necessary to enumerate all the advantages of the three-phase system, but it may be said that among the reasons for its universal adoption are that the three-phase generator is better than the two-phase generator for single-phase operation, where single-phase operation is required, and further, that the

three-phase generator when used as a single-phaser is practically as good and as cheap as it would be if it had been designed particularly for single-phase uses. Thus it can meet the two-phaser or the single-phase on equal terms in their own field and at the same time can afford its own special advantages.

When a three-phase generator is to be operated on a single-phase circuit, it is generally desirable to use a "Y" connected winding, although with certain types of windings the delta connection will give equally good results. With such a winding the three-phase machine, as ordinarily designed, will carry from 75 per cent. to 85 per cent. of its rated load in single-phase current between two conductors with the same heating which would be produced by operation at its rated capacity with balanced three-phase current. If motors or rotary converters are connected to a three-phase generator which is operating with single-phase load, these motors or converters will tend to equalize the load between phases and thus may increase the capacity of the system. When a three-phaser is partly loaded with single-phase currents between two of its wires, the unused phases may naturally be loaded with other single-phase currents, thus giving various degrees of unbalancing between the three phases and, with normal heating, will vary from 75 per cent. to 100 per cent. of the total three-phase capacity.

The statement that the three-phaser will carry 75 per cent. of its rated load in single-phase current frequently leads the customer to ask: "Why should I buy such a machine to deliver single-phase current when I can get a single-phaser which will deliver its full rated capacity with normal heating?" The answer to this question is that the three-phaser designed for a given single-phase output has about the same size and cost as the machine designed for single-phase alone, the apparent inconsistency lying in the fact that a three-phaser for a given output is cheaper and smaller than a single-phaser.

While purchasers of three-phase generators have frequently made special demand for large single-phase capacity, there are in point of fact, very few cases where it is necessary or desirable to operate three-phase machines exclusively on single-phase load. Companies that operate single-phase circuits can almost invariably divide their circuits roughly into groups, putting some of them on one phase and some on the others. The only portion of a lighting company's load which cannot be advantageously

divided between the phases is the low tension, interconnected distributing system, if such a system is used. Even where such systems are used they never include the whole lighting distribution of the company and there will always be outlying circuits which can be operated from other phases. There are also, in most cases, tranformers for arc lighting and other kinds of single-phase load which can be put upon the least used phases, and which will thus tend to help out the balance of the system. Many purchasers think that it is necessary to buy a single-phase generator because they use single-phase circuits, whereas the approximate division of these circuits between the phases would involve no difficulty whatever.

Since the normal single-phase capacity of a three-phaser is about 80 per cent., since all motors and rotary converters tend to equalize the balance, and since there is always scattering single-phase load which can be conveniently put upon the lightly loaded phases, we may practically consider that the three-phase generator can be used at its rated capacity on any system.

If the three-phase generator is operated with single-phase load, or with seriously unbalanced load, there will generally be a marked potential difference between its phases. The phase carrying load will show the drop in potential which such load would ordinarily occasion on a similar single-phase machine; one of the disused phases will generally show a higher voltage and the other a lower voltage. With machines of good inherent regulation, such as are now generally used for lighting purposes, these differences are small and can readily be taken care of by regulators in feeder circuits. Where three-phase generators are operated on single-phase, three-wire distributing systems, the general practice is to regulate the generator to give the desired voltage on the three-wire system, and to control by regulators the voltage of circuits connected to the other phases. The variations of voltage on these other phases may, in some cases, be actually a convenience, since between the three phases a voltage can often be selected which will nearly suit the requirements of any feeder.

Two systems of low tension distribution for lighting are used and recommended in connection with three-phase generators, viz.: the single-phase, three-wire system and the three-phase, four-wire system. When the single-phase, three-wire system is used, the generator is generally somewhat unbalanced by the large demand for single-phase current which the three-phase wire system creates,

and the voltage is regulated with reference to the needs of the three-wire system. The primary circuits are so arranged as to deliver power through transformers to low tension network. The transformer secondaries are provided with three leads, one for the neutral and one for each of the outside wires. Since the drop in high tension lines is small and since transformers can be put wherever they are needed, it is easy to arrange an alternating three-wire system in such a manner that it will give very perfect voltage distribution in all parts of the area which it supplies. In direct current, three-wire systems, we naturally have to deal with large and variable feeder losses, which, in spite of the most

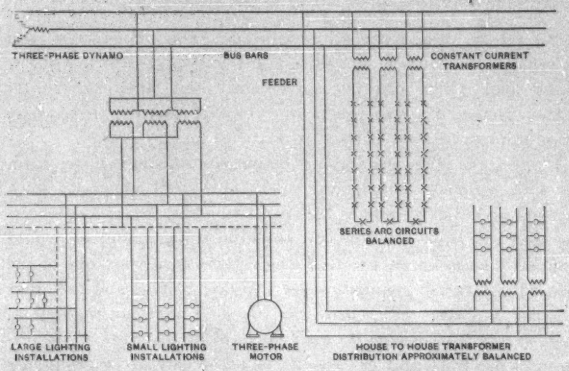

FIG. 1.—Four-wire three-phase low tension system,

careful arrangements, must seriously interfere with the maintenance of good regulation. In alternating three-wire systems the regulation should, with intelligent handling, be practically perfect.

The other method which is available for low tension distribution with three-phase dynamos is the four-wire, three-phase system. This system is supplied from groups of transformers, with three in each, their secondaries being connected in "Y" from a neutral. The secondary voltage of each transformer is that suitable for the lamps which it is desirable to use. In action, this arrangement is equivalent to the ordinary three-wire system, except that it has three branches and a neutral instead of two

branches and a neutral. The copper economy is practically the same in both, the advantage being slightly in favor of the four-wire, three-phase system, since the neutral need not be quite so large. This system also has the advantage that its outside wires are available for operating motors. Another advantage is that it affords a balanced load to the three-phase generators, if the four-wire system is kept in balance.

The arrangement of these methods of secondary distribution is illustrated by Figs. 1, 2 and 3. From these diagrams it will be

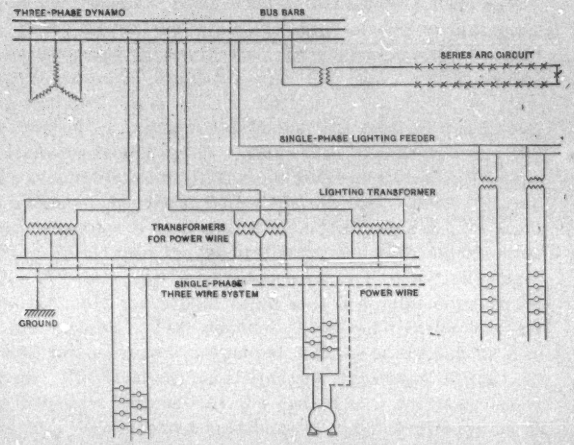

FIG. 2.—Three-phase generator with single-phase three-wire low tension system.

seen that it is necessary to use four wires with either, if motors are to be operated. Where the single-phase, three-wire system is used, it is necessary to run a separate power wire which can be energized from a transformer, and which, with the outside wires of the three-wire system, affords three-phase currents for operating motors.

The four-wire, three-phase system cannot be advantageously used in all cases. Where it can be consistently used on a large scale it is probably the most desirable method of secondary distribution. It should not be used, however, where the conditions are such that the three-phase system must be seriously unbalanced

by arc light transformers or other unavoidably unbalanced load. Generally it is not desirable unless its arrangement is complete and the whole plant is arranged and operated with reference to its use. In the rearrangement of existing plants it will generally be expedient to use the single-phase, three-wire system operated from three-phase generators as described above.

In distributing electricity over considerable areas it is desirable to keep in view certain general principles in order that proper voltage distribution may be obtained. Some of the variations which affect voltage regulation are controllable from the station, while others are beyond such control, and conse-

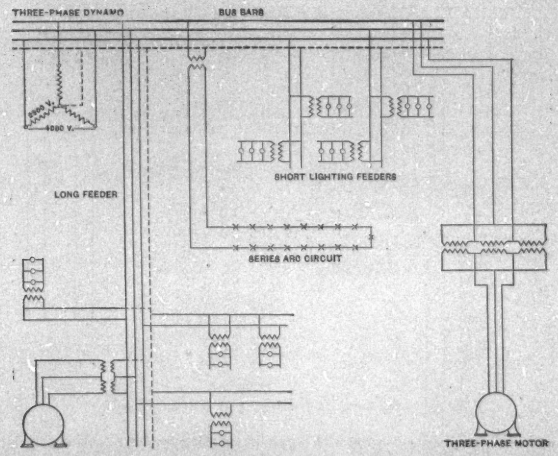

FIG. 3.—High tension four-wire three-phase system.

quently can be only partly equalized by the maintenance of a desirable average condition at the main station; even where controlling apparatus is provided in the main station the regulation may be imperfect unless considerable expense is incurred for labor necessary to the intelligent handling of such controlling mechanism. The following simple rules should always be kept in view when distribution systems are being arranged:

1st. Reduce the number of circuits to be regulated to a minimum. 2d. So arrange the system that variations not controllable

from the main station are made as small as possible. 3d. Reduce the amount of total drop on all circuits so that frequent changes will not be necessary. 4th. Interconnect the load in large groups so that any variable load unit will be small in comparison to the whole of which it forms a part.

The proper application of these rules will generally lead to an arrangement where the number of feeders is small, each feeder carrying the maximum amount of power which it is desirable to transmit over a single line. Each feeder will supply a compact primary network or a set of short primary branches, the loss beyond the feeder end being small so that a good voltage regulation at the feeder end will ensure good service to all the customers connected to that feeder. To get such a result the load must, of course, be connected near the feeder end instead of being scattered throughout its length.

A method of primary distribution has been used and advocated to a considerable extent which frequently lends itself very well to the accomplishment of the results above mentioned. This system is illustrated by the accompanying diagram. The "Y" connected generator is used with windings arranged to give about 2,300 volts between the neutral point and each outside wire. Such a generator may be loaded as if it were three separate single-phase machines, the neutral being used as a common return for all the circuits. The standard 2,300-volt transformers are adapted to use between the neutral and any of the outside conductors. The usual method of applying this system is to run out long four-wire feeders. At the end of each four-wire feeder there may be a loop or a branching of the four-wire system so that it is brought near to all parts of the area to be supplied. The transformers for lighting purposes are connected to short two-wire branches, which connect to the four-wire feeder at or near its end, the arrangement of these branches being such as to give an approximately balanced load on the four-wire system. If the load is balanced there will be no current in the neutral. Even if the unbalancing is considerable, the drop in the neutral will be so small that it will only slightly affect the voltage conditions. Regulators can be used in the main stations in each of the outside conductors, and these in combination with compensated voltmeters can maintain the desired potential at the feeder end between each of the outside conductors and the neutral. The neutral conductor should preferably be grounded in the

main station so that the maximum voltage to ground on any of the transformers will be 2,300 volts.

With a rough approximation to balance we virtually have, by this system, three-phase transmission at 4,000 volts, the voltage between the outside wires being about 4,000, when we have 2,300 volts between each wire and the neutral. The system thus affords means by which we can economically distribute over large areas without the use of step-up transformers.

When this system is used, it may often be desirable to operate lines in the immediate vicinity of the power station from single-phase branches instead of running out the four-wire feeders. The neutral should simply be used as a common return where convenient, and the long lines should be so arranged that the common return will be as effective as possible. Wherever motors are used it is, of course, necessary to get access to all three of the outside conductors.

The great improvements which have recently been made in automatically regulated three-phase generators have made it economical and desirable to use such machines in many cases where direct current apparatus would heretofore have been adopted. The alternator is simpler, more efficient and less liable to trouble than the direct current machine, and it is often desirable to use it even where long distance transmission is not required. There are also many cases where the principal loads are found in the immediate vicinity of the installation, but where there are certain long branch lines which it is desirable to operate at high voltage. If low tension alternating current generators are used, such transmission lines can always be taken care of by step-up transformers. The system recommended for such low voltage alternating distribution is the four-wire, three-phase system operated from a low voltage "Y" connected alternator. The winding of the alternator is such that the voltage of lamps is provided between its neutral and its outside wires. A four-wire network is supplied from the machines through suitable feeders, the lights being operated in approximate balance between the outside wires and the neutral, and standard motors being connected to the outside wires where desired. If the standard 220-volt motors are used the desirable lamp voltage will be about 125 and with 440-volt standard motors 250-volt lamps will generally be suitable. The system of distribution with the higher voltage can be extended

over considerable areas with small expense for copper, and is very desirable for mill lighting and many other purposes.

Such low voltage alternating work is desirable for railroad yards, summer hotel properties, colleges, private estates and other similar installations.

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[ADVANCE COPY—SUBJECT TO REVISION.]

DISTRIBUTION OF ELECTRICITY IN CITIES OF MODERATE SIZE.

BY WILLIAM LISPENARD ROBB.

In dealing with the question of the distribution of electricity it is impossible to lay down any but very general principles that will apply to many actual cases. Each individual case will be governed largely by existing local conditions. Much that would be desirable if a plant were being laid out new is found impracticable when the conditions of an existing plant are taken into account.

Cities naturally divide themselves into groups according to population, and for the purposes of this paper I have considered "cities of moderate size" as including those having a population of two hundred thousand or less. A satisfactory solution of the problem of electrical distribution is manifestly different in cities of this class from that in the large metropolitan cities.

Indeed, in dealing with the problem in cities of moderate size, a system of distribution that would be satisfactory for the smaller cities of the class would not meet all the requirements of the larger cities. No exact limitation can be placed as to the point at which the requirements materially change as they are largely governed by local conditions other than population. It seems to me, however, that cities having less than about 50,000 inhabitants make a class by themselves.

In cities of less than 50,000 inhabitants a very considerable area has to be lighted, in general extending out from two to three miles in all directions from the central station. In a con-

siderable portion of the city electricity will be required only for street lighting. Then fifty to one hundred miles of street will have to be lighted, and arc lighting will generally be required for this service. It will be necessary to supply electricity for incandescent and arc lighting and power wherever desired. In general, in the cities of this class there will be practically no tendency to put in isolated plants. There will be found little, if any, objection to overhead wires. If any wires should be required to be placed under ground it will be only in a very limited section of the city, and the total amount of electrical energy supplied from the underground wires would be small. The commercial lighting and power in a city of this class would not be concentrated but scattered over several square miles. The demand for variable speed motors would be too small to be taken into account. The total amount of electrical energy would be too small to warrant the maintainance of more than a single station.

Under all these conditions it seems to me that only three-phase alternating current, having a frequency of 60-cycles and under a pressure of about 2,300 volts should be generated.

The street arc lighting should be by constant current series enclosed arc lamps. The distribution for lighting would in general be single phase, and if motors of three H. P. or under, only were used, it would be best to operate the motors from the single-phase lighting system. My own experience has been that single-phase motors above this size are not satisfactory as compared with polyphase motors, and will not meet all the requirements. Any city central station should be capable of supplying power for any purpose, and should be able to supply current for electrolytic and storage battery work. When the motors required are large, three-phase motors should be used, and three-phase rotary converters installed on the customer's premises should be used for electrolytic purposes.

The city should be divided into sections, and the different sections supplied from the different phases. If at any one point in any section large motors or rotary converters are required the additional primary wire would be brought from the nearest point in the adjoining section. Satisfactory service will be given with light and motors supplied from the same circuits.

In sections where there is any concentration of lighting and power a 220-volt three-wire system of secondary wiring should

be used, and be supplied if the system is small from a single transformer, or if the system is large, from transformers suitably located at several points. I do not think it would be found desirable in practice to cut out any of these transformers during the hours of light load.

In the larger of the cities of moderate size a different set of conditions exist, and the problem of electric distribution is very materially modified. The area lighted is very large, and while commercial lighting and power is concentrated in sections, lighting and power service has to be supplied in practically all parts of the city. There is a tendency for the department stores, office buildings and large manufacturing industries to put in their own electric plants, and there is a growing demand for the wires in the business section to be put underground.

In cities of this class there are generally two sections where the demand for electricity is concentrated—the business section where are located the large stores and office buildings and the manufactoring district. Each of these sections has its own characteristics. In the business district the use of the large motor is largely confined to elevator and other service where the load is exceedingly variable and intermittent, and at the same time the very best lighting service is insisted upon, both as regards the constancy of the lights and the absolute certainty of the service. As a rule in the manufacturing district the percentage variation in load on the motor service is very much less than in the business section, the only variation that seriously affects the lights occurring when the machinery is started in the morning and after the noon hour. At these times there is practically no lighting. While the demand that the wires in the business section should be placed underground must be heeded, there is practically no demand for it in manufacturing districts.

The central station should be located at a point where coal can be delivered directly from the boat or railroad, and where water for condensing can be readily obtained. In nearly all places, this means that the generating station will be situated a considerable distance from the business section of the city. The conditions existing in the business section of a city of this class, as against the concentration of load, the intermittent character of the motor load, the necessity and desirability of underground wires, the existing investment of central station and customers in direct current apparatus, isolated plants, and the relatively

high price charged at present for alternating currents and arc lamps, motors, etc, make it desirable to supply the business section at the present time with direct current.

Considering that it is desirable to supply both commercial, incandescent, and arc lighting and also motors from the same system of wiring, it seems best that the current should be distributed on the three-wire-220-volt system. This voltage is preferable to a 440-volt system, as in my opinion the saving in copper required for the distribution, if the higher voltage is used, is much more than counterbalanced by the inferiority of the 220-volt arc and incandescent lamps as compared with the corresponding 110-volt lamps.

In general, the situation of the power-house most suitable for the cheap production of electricity will not be in the business district. The needs of a city of moderate size would also not justify the operation of two power-houses. The electricity for the business district should be therefore in general be supplied from a rotary converter sub-station, situated as near as possible to the center of distribution of the business district.

The main power-house should generate only alternating current. This should have a frequency of 60-cycles, be a three-phase four-wire system, and have a pressure of approximately 2,300 volts between each phase wire and the common wire. The four-wire three-phase system is preferred, owing to the saving of copper, over other systems that would prevent the using of standard 2300-volt transformers and other standard line materials. Sixty cycles should be used, as arc lamp motors, incandescent lamps and rotary converters for supplying the 220-volt direct current, can all be operated satisfactorily at this frequency, and at no other frequency at which generators are now made commercially.

The electricity from the power-house to the rotary sub-station should be transmitted on the three three-phase wires, the common fourth wire being omitted. Boosters would not be required, and the pressure in the D. C. side of the rotaries would be varied by means of the static transformers used in connection with the rotaries.

The direct current distribution from the sub-station should be underground. Not only is this demanded by the public, but in the business section of the cities, I believe that interest or investment cost of maintainance taken into account, it is decidedly cheaper as well as much more satisfactory to maintain an underground than an overhead system of distribution.

The feeders should be lead-covered cables drawn into conduits. As feeders are liable to have for short periods considerable overloads, and there are no branches to be tapped off. I believe paper insulation is more satisfactory as well as cheaper for feeders than rubber.

The distribution boxes should be of the manhole type, or better still, of the lamp post type. The old style of Edison box blocks traffic too much to be installed at the present time.

When frequent services have to be made there is nothing so satisfactory as the old Edison tubes. When the services are infrequent the most satisfactory system is to use lead-covered rubber insulated cable drawn in ducts as distributing mains, carrying a single service into each building, from a small distributing box placed at every other property line. Arc lighting, incandescent lighting and power should all be supplied from the same system of distribution.

Outside of the business section the electricity should be supplied for all purposes on the alternating current system. The current should be taken to the power-house from various distributing centers on the four-wire three-phase system. From these centers of distribution single phase circuits should be run for the operation of commercial arc and incandescent lighting and small motors. Additional phase wires would have to be taken from the centers of distribution to manufacturing plants where large motors were used.

When the lighting is at all concentrated the lighting and motors should be supplied from three-wire 220-volt secondary mains, fed by large transformers, and it will be found desirable to thoroughly ground the neutral wire.

The street lighting should be by series constant current arc lamps. In some cases it would be desirable to supply the current for these from transforming devices located at the central power-house. In other cases the transforming devices could be most advantageously located at the centers of alternating current distribution, as thereby the number of wires could be materially reduced, a few large wires taking the place of a very much larger number of small wires.

In order that a system of alternating current distribution of any size should be satisfactory, it is necessary that the arrangement of the power-house be such that current be supplied to the different feeders at different pressures. This can be done by

boosting transformers in each feeder circuit, and by a system of pressure wires brought back to the power-house from the various centers of distribution, or by the automatic device of Mr. W. L. R. Emmet.

The successful introduction of the Nernst lamp into the fields of incandescent and arc lighting, and the development of the steam turbine should have a marked effect in favor of the generating and distribution of alternating current. On the other hand, the air is full of rumors of marked improvements in storage batteries.

A paper read at the 158th Meeting of the American Institute of Electrical Engineers, New York and Chicago, November 22, 1901.

[ADVANCE COPY—SUBJECT TO REVISION.]

250–500 VOLT THREE-WIRE DISTRIBUTION FOR LIGHTING AND POWER.

BY PHILIPPO TORCHIO.

In the last few years great improvements have been made in the manufacture and selection of incandescent lamps. The arc lamp practice has undergone a radical change. The wiring and appliances connected with electric installations of buildings and other places have been brought up to a high standard of good workmanship and insulation. These, and other not less important improvements have made possible the use of commercial voltages considerably higher than were permitted in the early stages of the industry of electric lighting and power distribution.

In existing well-developed systems of low-tension current distribution it would be out of the question to consider at this date the proposition of changing the voltage of the existing systems, but on new installations and in places where changes of systems of distribution are contemplated it is sometimes convenient to adopt the three-wire 500-volt system which has met with great favor abroad and especially in England, and which is gradually being introduced in this country. In its favor are the following points:

The system has all the advantages of the original low-tension Edison three-wire system, and it has greater capabilities of expansion in lightly loaded or scattered territories as is often the case in small cities or in large factories and other places. The system is economical to operate, it is economical as to distribution within a wide radius, it is flexible and easy of control and

simple of operation, and free from such troubles as capacity and inductive effects which appear on A. C. transmission lines and translating devices; it can be applied directly to a greater variety of services than any other system, and finally it derives from the use of the storage battery economical advantages in station investment and the invaluable commercial superiority of ensuring continuity of service.

The generating equipment and the station apparatus for 500-volt systems is just as well developed as any other apparatus on the market, and the cost is well in line with other standard apparatus.

The main unfavorable points of the 500-volt three-wire system are (*a*) the increased tendency to arc, necessitating the use of wiring and appliances of high insulation and carefully separated terminals at the customers' installation, (*b*) the lower efficiency of the 250-volt incandescent lamps as compared with lamps of half that voltage, (*c*) the difficulty of operating 250-volt arc lamps.

These limitations are gradually becoming less and less restrictive, as a review of the present conditions will demonstrate.

As to the insulation requirements for wiring and appliances, the new rules of the National Board of Underwriters prescribe the same insulation and breakdown test for all wires used with voltages between 0 and 600; all lamp sockets and receptacles must be suitable for use on any voltage up to 250 volts, only rosettes, cleats, knife and snap switches, etc., are required to be special for voltages between 250 and 600. In general, it may be said that any modern installation will safely withstand a 500-volt service, and that the conservative requirements of the Board of Fire Underwriters are not uncommercially stringent. It may, however, be said that not all the local Boards of Fire Underwriters have as yet adopted the rules of the National Board.

In regard to efficiency of high voltage incandescent lamps, the difference for the standard 16 C. P. lamp of same candle hour area as the low voltage lamp is about 10 per cent. The best 200–250-volt 16 C. P. lamps made at present, have an initial efficiency of 3.4 watts per candle, and have the same life as the 3.1 watt per candle 110–125-volt lamp.

In large cities supplied by Edison system, the common practice is to use lamps of 3.1 watts per candle; in all other places, lower efficiency lamps are ordinarily used, and the 3.6 watts per candle lamp is quite common. In the latter case the adoption of

a 3.4–3.5 w. p. c. 250-volt lamp would not materially overtax the user, nor the illuminating company, and therefore, for such places the 500-volt three-wire system would not be at a disadvantage on that account.

The difficulty of adapting arc lamps to the 500-volt three-wire system has been overcome by connecting two ordinary enclosed arc lamps in series in the same manner that the old open arcs were, and are still, in many places, connected on the 110-volt circuits. Lately, however, several types of double arc lamps have been used with entire success. The single arc has also been tried to some extent, but it has proved a failure for general use on account of the objectionable blue light it gives. Such lamps are, however, used for street lighting in a few places.

The review of the difficulties to be overcome shows that they are not very serious, especially for new installations and where changes of distribution are contemplated.

In some calculations recently made to show the economic relations between this system and the ordinary 250-v. three-wire system it was shown that the savings are very large for lightly loaded districts. In the following table (I) are given the different assumptions made and steps followed in the calculation, which were as follows:

First column gives density of distribution per foot of street—*i. e.*, watts maximum load per foot of street.

Column (I) gives total length of streets covered by mains per square mile, to which unit are referred all following calculations. The assumption was made that in American cities there are on the average 25 miles of streets built per square mile of territory, exclusive of parks and open places. In the business and crowded sections it was assumed that practically all the streets are covered by mains. In less dense districts only a portion of streets are so covered by mains.

Column (II) gives the maximum load per square mile as obtained from the previous assumptions.

Column (III) shows one layout of feeders which might be representative of common practice for an ordinary 250-v. three-wire system. This is done to arrive at the length of mains to be supplied from each feeding point, as shown in column (VI), assuming conditions given in columns (IV) and (V).

Column (VII A) gives maximum amperes per outlet of mains.

TABLE I.

Watts max. load per foot of street covered by mains.	I. Length of streets covered by mains per square mile.		II. Maximum load per square mile.		III. Feeders required for 250 V. 3 W. distrib. with 660 A. density per 1,000,000 C. M.		IV. Average Feeding Points.		V. No. of Outlets.		VI. Average feet of mains per outlet.	VII. A. Amperes max. per outlet of mains 250 V. 3 W. distrib.	VIII. A. Average cross section of mains used if no large motors were conn. 250 V. 3 W. 1.6% Regulation = 4 V. over 250 V. c. m.
	Miles.	Feet.	K. W.	Amp. at 250 V.	No.	Average Size C. M.	Per Feeder.	Total.	Per Feeding Point.	Total.			
2.5	12.5	66,000	165	660	4	250,000	3	12	3	36	1,835	18.4	92,500
5	12.5	66,000	330	1,320	4	500,000	3	12	3	36	1,835	36.7	185,000
10	18¾	99,000	990	3,960	12	500,000	2	24	3	72	1,375	55.0	208,000
20	25	132,000	2,640	10,560	24	666,000	1	24	4	96	1,375	110.0	416,000
40	25	132,000	5,280	21,120	32	1,000,000	1	32	4	128	1,030	165.0	468,000
80	25	132,000	10,560	42,240	64	1,000,000	1	64	4	256	515	165.0	234,000

Watts max. load per foot of street covered by mains.	CONTINUED. IX. A. Lbs. of copper for 3-cable mains 250 V. 3 W. dist..	X. A. Lbs. of copper saved if 500 V. 3 W. dist. were used (75% of IX. A.)	XI. A. Annual saving at 25c. per lb. of copper in Cable and 7% Int. and Dep.	VII. B. Max. current allowance for large motors connected above normal current of column VII. A.		VIII. B. Average cross section of mains used if large motors were conn. 250 V. 3 W. 1.6% Regulation = 4 V. over 250 V. c. m.	IX. B. Lbs. of copper for 3-cable mains 250 V. 3 W. distrib.	X. B. Lbs. of copper saved if 500 V. 3 W. dist. were used (75% of IX. B.)	XI. B. Annual saving at 25c. per lb. of copper in Cable and 7% Int. and Dep.
				Amps. at 250 V.	K. W.				
2.5	54,945	41,208	$721	18.4	4.6	185,000	103,890	82,416	$1,442
5	109,890	82,416	1,442	18.4	4.6	277,500	164,835	123,624	2,162
10	185,328	138,996	2,432	27.5	6.9	312,000	277,992	208,494	3,648
20	494,208	370,656	6,486	55.0	13.8	624,000	741,312	555,984	9,729
40	555,984	416,988	7,297	82.5	20 6	702,000	833,976	625,482	10,945
80	277,992	208,494	3,648	165.0	41.2	468,000	555,984	416,988	7,297

Watts max. load per foot of street covered by mains.	CONTINUED. XII. Square miles of Territory covered by one distrib. station.		XIII. Estimated saving of substation per square mile of 500 V. 3 W.	XIV. Annual saving Int. and Dep. at 6% and taxes at 2%	XV. Annual saving of operation per sq. mile of 500 V. 3 W	XVI. A. Total annual saving per square mile XI. A. + XIV. + XV. without large motors.	XVI. B. Total annual saving per square mile XI. B. + XIV. + XV. with large motors.	XVII. Total K. W. Hours delivered per square mile at the load factor marked.		XVIII. Total saving per K. W. Hr. delivered.	
	250 V. 3 W.	500 V. 3 W.						L. F.	K. W. Hrs.	Without large motors.	With large motors.
2.5	4.	16	$6 250	$500	$750	$1,996	$2,717	20%	289,080	.692c	.940c
5	4	16	7,812	624	750	2,816	3.537	20%	578,160	.488	.612
10	2	8	15,625	1,248	1,500	5,180	6,396	25%	2,168,100	.239	.295
20	1	4	31,250	2,496	3,000	11,982	15,225	25%	5,781,600	.207	.263
40	.75	3	50,000	4,000	4 000	15,297	18,045	25%	11,563,200	.132	.156

Column (VIII A) gives cross section of each outlet for 1.6 per cent. regulation, assuming its load evenly distributed.

Column (IX A) gives the weight of copper required for mains as determined for the above cross sections.

In column (X A) is given the saving of copper which would be realized if a 500-v. three-wire system had been used instead of the 250-v. three-wire, for same conditions in both instances.

Column (XI A) reduces the copper saving to saving per annum on an assumed basis of cost of copper in case of underground cables, which cost includes a rough estimate of the cost of insulation and lead sheet. In case of overhead lines this saving should have been about one-third less.

In columns (VII B), (VIII B), (IX B), (X B), (XI B) are given on similar lines the calculations of savings for systems operating motors from the lighting mains, assuming to maintain the same regulation of 1.6 per cent. for the specified momentary inrush of current due to motors for each main. This calculation is not accurate, but will not materially offset the relative results under discussion.

Column (XII) gives an estimate of the territory which can be economically covered by a low-tension station, so as to arrive at the savings of station investment. Only a few years ago, before the introduction of the rotary and inverted rotary converters and composite D. C. and A. C. generators, it would have been impossible to concentrate in one station the production of current for the whole system, and therefore, to study the general problem which we have now under discussion, it would have been necessary to introduce the consideration of building and operating separate L. T. generating stations to cover a certain limited territory. This is no longer the case, as only in comparatively few cases in the lighting situation will it pay to operate more than one generating station, except in the case of very large cities covering hundreds of square miles of territory. Under the present conditions the determination of the number of distributing sub-stations is only a matter of balancing the cost of L. T. feeders and other factors entering the cost of distribution against the extra cost at a new sub-station and its operation. Under column (XII) is given a rough approximation of the square miles of territory that could be economically supplied by L. T. sub-stations under given conditions. It will be noticed that with a 500-v. three-wire system a sub-station can in each case supply for same current density in feeders

and same regulation a territory four times as large as with a 250-v. three-wire system. Under these conditions, which are approximately the most economical, the amount of copper for feeders will *be the same for both systems.* There will, therefore, be no saving of copper for feeders in favor of the 500-v. system. While no feeder saving is effected by the 500-v. system, a large saving will be made by the reduction of the number of substations and their operating expenses, which savings per annum are estimated as given in columns (XIV) and (XV).

The following columns (XVI A) and (XVI B) give the sum of all savings, and the last two columns the same, prorated to each K. W. hour delivered for specified commercial load factors:

TABLE II.

Watts Max. Load per foot of Street covered by Mains.	Copper Investment Saving. X. A. No Large Motors.	Copper Investment Saving. X. B. With Large Motors.	Est. Saving of Substation. XIII.	Total Investment Saving. A. No Large Motors.	Total Investment Saving. B. With Large Motors.	Total Investment Saving per K. W. Max.	
						A. No Large Motors.	B. With Large Motors.
2.5	$10,302	$20,604	$6,250	$16,552	$26,854	$100 00	$162 50
5	20,604	30,906	7,812	28,416	38,718	86 00	117 00
10	34,749	52,123	15,625	50,374	67,748	51 00	68 50
20	92,604	138,906	31,250	123,914	170,246	47 00	64 50
40	104,247	156,370	50,000	154,247	206,378	29 20	39 20
80	52,123	104,247	100,000	152,123	204,247	14 40	19 40

In these calculations we have assumed that the station machinery would have the same unit cost per K. W. capacity in both systems. The total capacity will be the same in both cases.

We have not taken into account the question of subway ducts, as we have assumed the cost of distributing ducts to be independent of the size of mains. In the case of trunk ducts for feeders we have assumed to require the same number of duct feet in both cases. This will not be the case in actual practice, as while with the two systems we have the same amount of copper to lay in ducts, still in the case of 250-v. system this copper can be better distributed in large cables to fill up the whole duct capacity, while in the case of 500-v. system the copper must be distributed in smaller cables, which cannot be made to utilize as fully the capacity of the ducts. This fact would offset some of the savings for the 500-v. system given in the table.

In the case of overhead lines it has already been noted that the savings for copper would be about one-third less than given in

the table. Furthermore, in actual practice the size of 500-v. mains would usually be selected with a more liberal margin than for the 250–v. mains. Therefore, the savings given in table represent the *maximum theoretical savings in favor of the* 500–v. *three–wire system* under the specific conditions therein assumed.

These savings are greater in lightly-loaded districts, where we have already stated that, in general, low-efficiency lamps are more suitable. Therefore, if the efficiency and life of 200–250-v. lamps are practically the same as for the low-voltage lamps, the company can supply the same number of lamps of the two types per K. W. capacity of station machinery and distributing feeders and mains; the customer will consume the same amount of current for the same amount of light, and therefore the savings in favor of the 500-v. three-wire system given in the previous table represent actual net savings to the company. If the system has arc lamps and motors connected the saving per K. W. hour delivered for those classes of services will also be net savings to the company.

It will be found that in general these conditions are mostly common in the out-lying districts of large cities and in the majority of small towns. In many of these cases I think that a 500-v. three-wire system would be entirely successful and present economical advantages. A further advantage in these cases is the relative large saving in investment per K. W. added in favor of the 500-v. system over a 250-v. system. This is shown in table (II), obtained from the data of the previous table.

The savings in investment in lightly-loaded districts go up in the hundreds of dollars per K. W. load added, and if the district is not expected to reach higher densities it is clear that the advantages of a 500-v. three-wire system are very great, especially if, as is often the case, there is a considerable number of small motors for residence elevators and small factories and shops, but not sufficient to warrant the installation of a separate power circuit to cover such a scattered territory.

In heavier loaded districts the savings are considerably smaller, and represent an insignificant proportion of the total business, as shown in table (I), comparing the total savings of columns (XVI A) and (XVI B) with the total K. W. hours sold, as per column (XVII). Besides, in larger systems, it is important to u the most efficient lamp which can be commercially operated, and

this further consideration excludes the use of high-voltage lamps, independently of any consideration of the difficulties and expenses involved in the proposition of readjusting to the higher voltage the existing station machinery, storage batteries and switchboard equipments, and also the customers' installations of arc lamps, motors, and a large proportion of wiring and appliances.

The 500-v. three-wire system has found a special favor in England, principally on account of the local practice of not supplying customers with free renewal of lamps, which has created a condition where only low-efficiency lamps could be operated satisfactorily. Few lamps in England, only three or four years ago, had a higher efficiency than 4 w. P. C. Most lamps in use were old lamps of an efficiency of 5, 6 or 7 w. P. C., and in many cases companies started off with free new 250-v. lamps at 4 w. P. C., giving a positive saving. The 500-v. system has been adopted in several places in this country, among which the most prominent instance is the system of the Narragansett Electric Light Company, of Providence, R. I., operating a 470-v. three-wire system. The experience of this company has unquestionably proved the practicability of the 500-v. three-wire system in small cities and towns under conditions existing in America.

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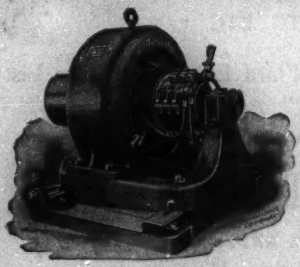

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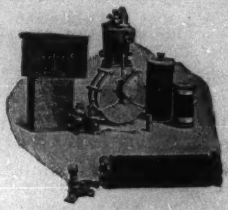

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